Development of Remote-Sensing Microwave Radiometer Calibration Methods and Tools at NIST

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Outline

- **Motivation: Cal/Val support for microwave remote-sensing radiometry community**
- What does "traceability" mean?
- Standard radiometers and cal targets
- Uncertainty analyses and specifications
- Standard terminology "dictionary"

IORD Content Example

Sea Surface Temperature (SST)

- Sea Surface Temperature is defined as a highly precise measurement of the temperature of the surface layer (upper 1 meter) of ocean water. It has two major applications: 1) sea surface phenomenology, and 2) use in infrared cloud/no cloud decision for processed cloud data. The accompanying requirements apply only under clear conditions (unless specified otherwise).

Systems Capabilities	Thresholds	Objectives
a. Horizontal Cell Size		
Nadir, clear	1 km	0.25 km
Worst case, clear	1.3 km	
All Weather	40 km	20 km
b. Mapping Accuracy		
Nadir, clear	1 km	0.1 km
Worst case, clear	1.3 km	
All Weather	5 km	3 km
c. Measurement Range	-2° to 40° C	-2° to 40° C
d. Measurement Precision		
Clear	0.2° C	0.1° C
All Weather	0.3° C	0.1° C
e. Measurement Uncertainty		
Clear	0.5° C	0.1° C
All Weather	1.0° C	0.5° C
f. Refresh	6 hours	3 hours
g. Long-Term Stability	0.1° C	.05° C
h. Latency	90 minutes	15 minutes
i. Geographic Coverage	Global Ocean	Global Ocean

(Courtesy NPOESS IPO)

"Traceability:"

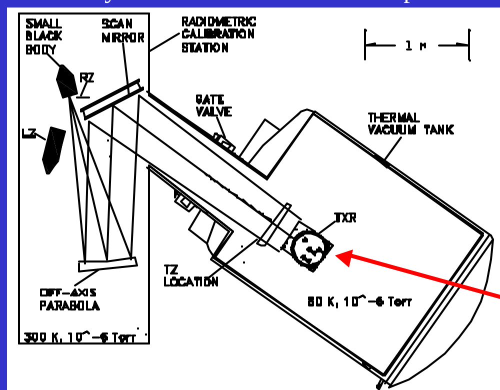
- "Property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties." (ISO VIM, 2nd ed., 1993, definition 6.10)

- Only *measurements* are traceable; not instruments, calibration reports, or laboratories
- *Establishing* traceability is the responsibility of contractors and users
- *Verifying* traceability is the responsibility of NIST and other standards laboratories
- Ref: http://www.nist.gov/traceability/

Thermal-infrared Calibration Issues—NIST OTD

- 200 K to 350 K blackbody usually used as the standard of radiance.
  - –Each calibration facility makes their own blackbody.
  - –NIST traceability is claimed but for thermometers only.
  - –Emissivity modeled but not measured.

- Usually the chamber environment provides unwanted background sources.



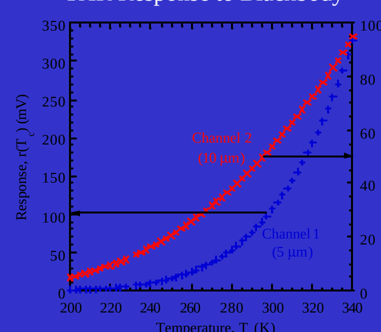
<u>NIST Solution:</u>
Measure blackbody radiance *in-situ* with a Thermal-infrared Transfer Radiometer (TXR)

<u>Example:</u>
NIST TXR at Los Alamos National Lab. Cal. Facility

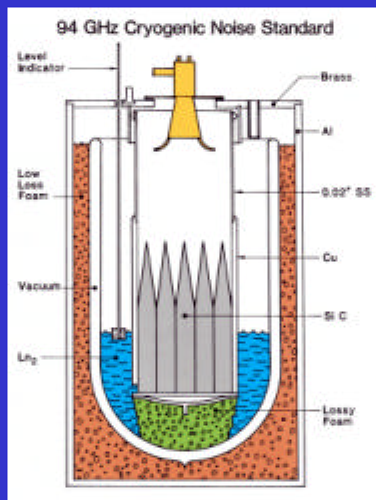
Calibration of TXR at NIST OTD

- Used TXR in Medium Background IR (MBIR) facility at NIST.
- Shroud can be cooled to 80 K or left at room temperature.
- Viewed 11 cm diameter cryogenic blackbody (BB).
- Radiance scale is currently from temperature sensors in blackbody.

TXR Response to Blackbody

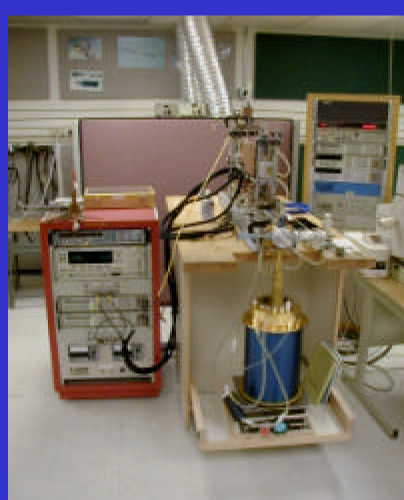


NIST Primary Noise Standards



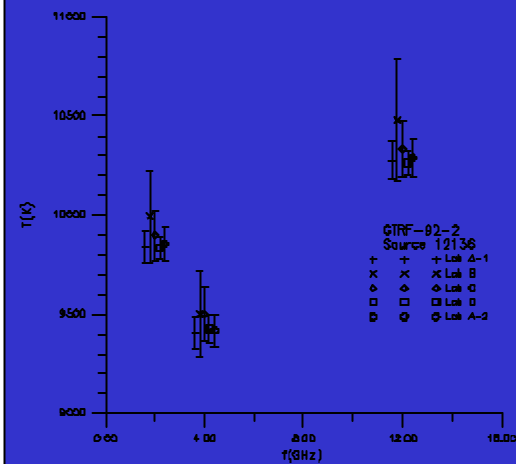
- Link to primary microwave noise standards
  - Well-characterized primary standards used for decades
  - Stable reference for long-term geoscience studies
- Practical Examples
- Discussion and Recommendations

Thermal Noise Calibration



- Linked to primary microwave noise standards
  - Well-characterized primary standards used for decades
- Typically used to calibrate commercial noise sources (e.g., diodes, gas tubes)
- Comprehensive uncertainty analysis
  - 0.11% std. uncertainty from 200 K to 300 K (~0.3 K)
  - ”traceable” measurement

International T_N Comparisons



- US, France, Germany, and UK
- 2, 4, and 12 GHz solid-state sources
- Measurements agree within quoted unc. of 0.5% to 2.9%
  - Techniques correct
  - Unc. analyses correct

NIST NOISE

Near-Field Antenna Calibration

RF Fields Group

- Planar, cylindrical, and spherical measurements
- Far field calculated from near-field measurements
- Fixed-frequency gain ±0.10 dB up to 26 GHz
- Antenna patterns ±0.05 dB/dB up to 26 GHz
- Currently performing calibrations up to 75 GHz; up to 110 GHz in development

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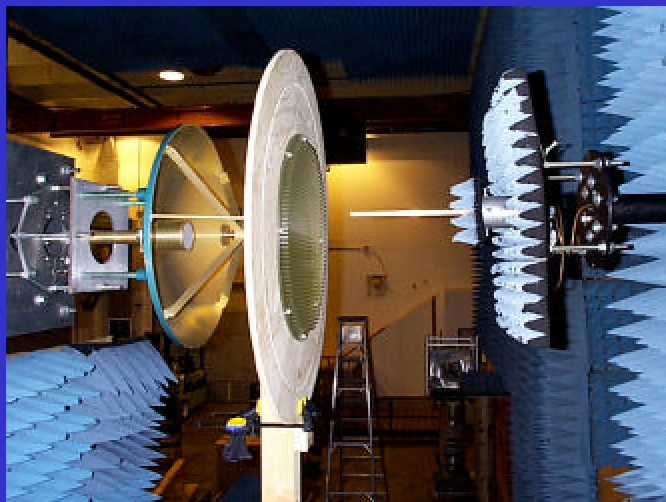
NOAA Quarter-Wave Plate Measurement



"Evaluation of a Radiometric Phase Retardation Plate Using Planar Near-field Measurements", F2 Remote Sensing of the Atmosphere II

NIST NOISE

NIST Microwave Radiometry Cal R&D

- Standard radiometers covering µw and mmw bands up to 65 GHz
- Standard portable calibration targets covering up to 65 GHz; possibly 110 GHz
- Uncertainty analyses and specifications
- Standard terminology "dictionary" for microwave remote-sensing radiometry

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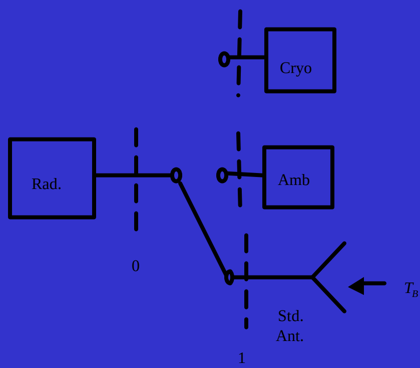
Configuration for Standard Radiometer



$$T_B(q,f) \equiv \frac{l^2 B_f(q,f)}{2k}$$

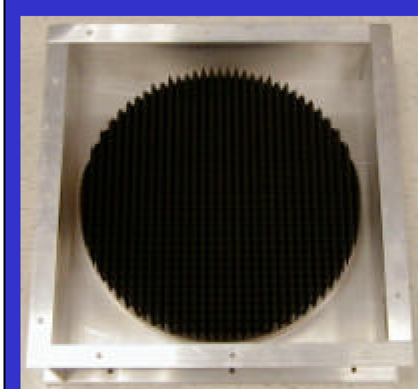
$$P = kT_{A,in}\,Df$$

$$T_{A,in} \equiv \frac{A_{eff}}{l^2} \int_{4p} T_B(q,f) F_n(q,f) dW$$

$$\overline{T_{ML}} = \frac{1}{a h_M} T_{A,out} - \frac{(1-h_M)}{h_M} \overline{T_{SL}} - \frac{(1-a)}{a h_M} T_a$$

Estimated uncertainty in $\overline{T_{ML}}$ ~ 0.3 to 0.8 K for T=200-300 K

Standard Calibration Targets



- Portable standard targets up to 65 GHz; possibly 110 GHz
- Microwave and thermal characteristics measured
- Standard radiometer(s) used for microwave characterization
- Post-doc arriving in Jan. ’04 to develop targets

Uncertainty Analyses & Spec's

- General uncertainty analysis for total-power radiometers
  - Representative radiometer (or class) as a start
- Video detector (tunnel diode) nonlinearity
- Calibration target reflectivity effects

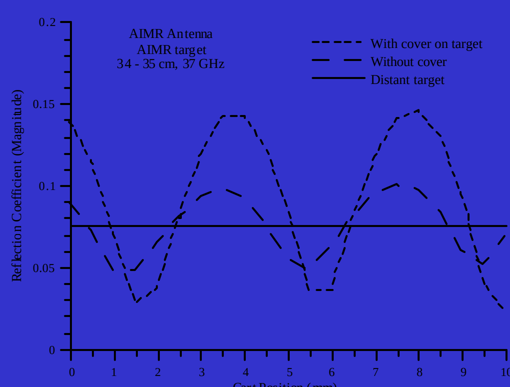
Calibration Target Reflectivity

- Evaluate error caused by ? G at antenna output due to "close-coupled" cal target
- Two effects:
  - Mismatch factor
  - System NF and $G_{avail.}$ (if no input isolator)

AIMR* target/antenna evaluation

*On permanent loan to NCAR
from the Canadian Ice Service

AIMR* target/antenna evaluation



$$u_{tot}^{(0)} \approx \sqrt{2}\,|X_{12}|\,|DG|_{RMS} \approx 5.2\,K$$

Over range of T = 200-300 K

-Note: with an isolator, this reduces to about 1 K

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Near-Ambient Noise Standard

- Check of how well our radiometers can measure near-ambient temperatures
- 263 to 325 K; 8-12 GHz
- Systematic uncertainty of measurement: ±0.3 K
- Absolute average deviation over temp. range at 8 GHz: ±0.054 K

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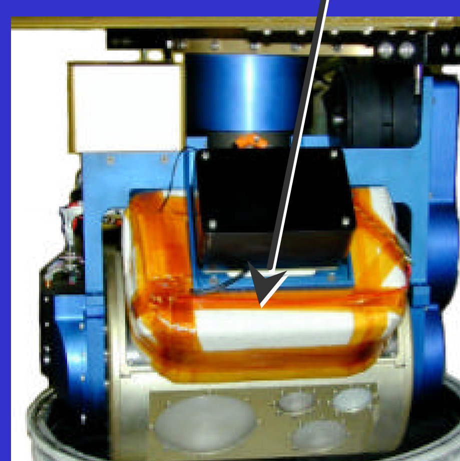
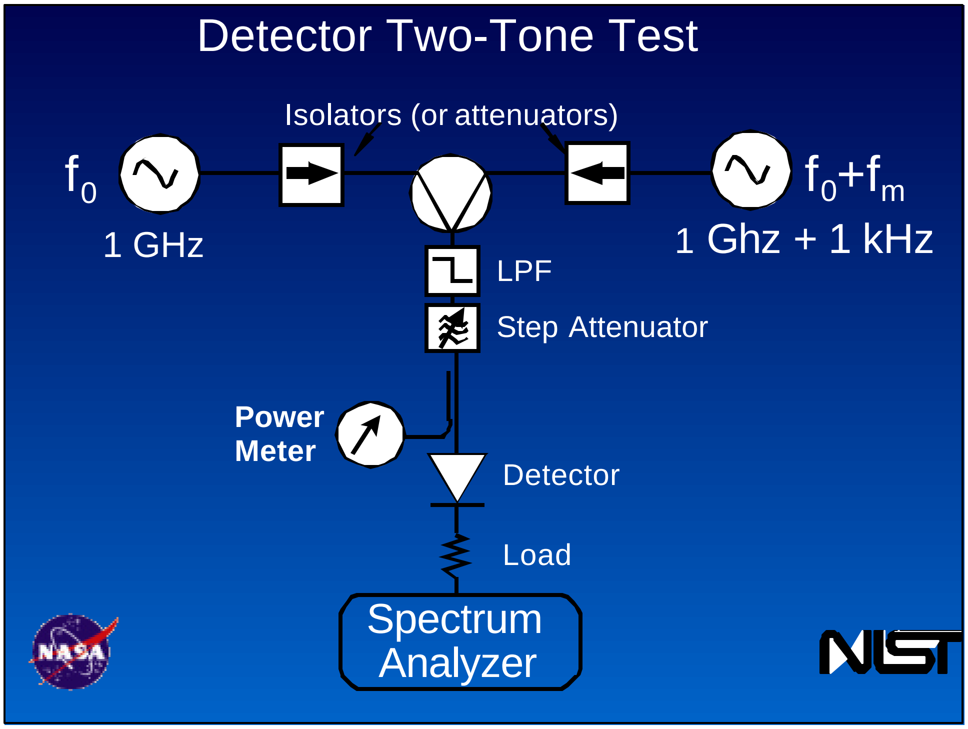
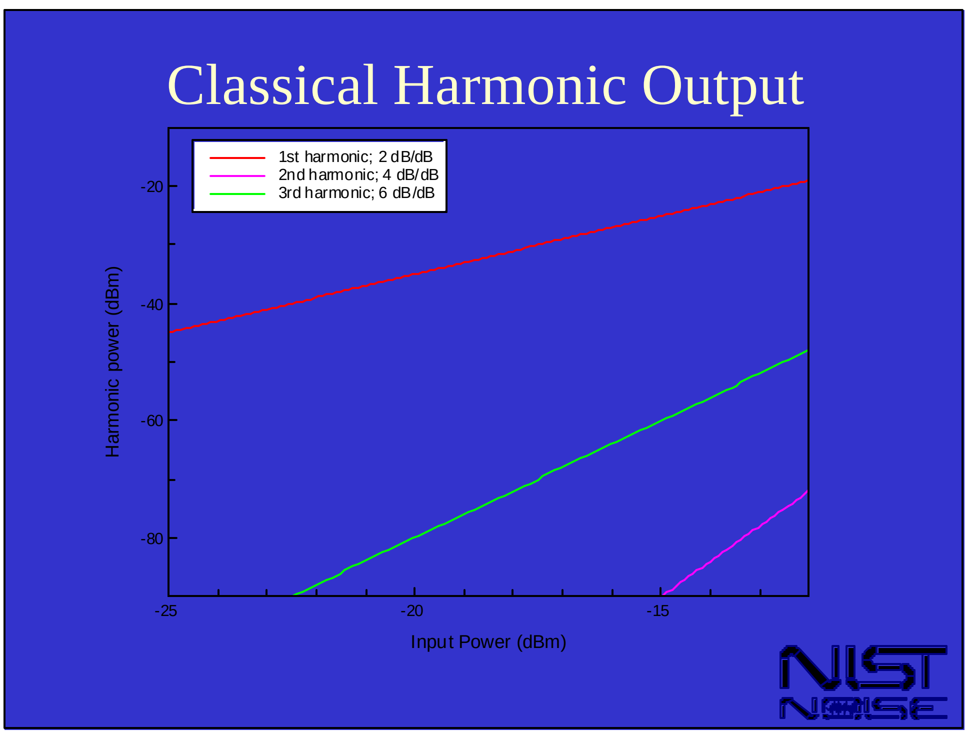
Calibration System

- ~1/2 K absolute error
- Periodic cal: ~5 sec
- External calibration targets
  - Iron/epoxy absorber on aluminum substrate
  - Hot load: heated to ~328K
  - Ambient load – 240-250K
- Close coupling of targets
- Thermometry
  - 8 RTDs on each calibration target – <0.05 K accuracy
- Post flight averaging using optimal filter
- Post processing correction of a/c pitch and roll variations

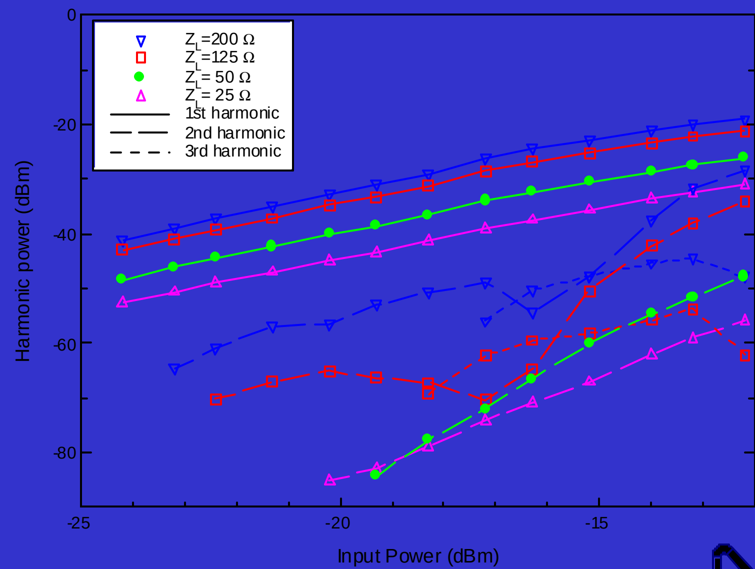
External Calibration Target




Detector Two-Tone Test
Isolators (or attenuators)
f_0
1 GHz
f_0+f_m
1 Ghz + 1 kHz
LPF
Step Attenuator
Power Meter
Detector
Load
Spectrum Analyzer


Classical Harmonic Output
1st harmonic; 2 dB/dB
2nd harmonic; 4 dB/dB
3rd harmonic; 6 dB/dB
-20
-40
-60
-80
Harmonic power (dBm)
-25
-20
-15
Input Power (dBm)

Detector Harmonic Output



Predicting ? T Due to Nonlinearity

- $\hat{T}=T_c+[(T_h - T_c)/(V_h-V_c)](V- V_c)$
- Quadratic approximation:

  $V ? P-CP^2$
- Worst-Case Interpolation Error:

  $? T =(C/4)\ (T_h - T_c)/(P_h-P_c)]$
- Worst-Case Extrapolation Error:
  - Use Point-Slope eq'n; include C_h and C_c

Ref: Reinhardt *et al.*, IEEE Trans. MTT, April 1995.

CoSMIR Radiometer Overview

Center Frequency (GHz)	IF Bandwidth (MHz)	Noise Figure (dB)	Sensitivity 100 ms int. (K)
50.3	400	4.8 (SSB)	0.13
52.8	400	4.8 (SSB)	0.13
53.6	400	4.8 (SSB)	0.13
91.655	1000	6.5	0.10
150.0	1000	10.5	0.30
183.31±1	500	7.8	0.30
183.31±3	1000	7.8	0.21
183.31±6.6	1500	7.8	0.17

Examples of Predicted ? T

	T_h	T_c	T range
CoSMIR T_N=500 K	325 K	245 K	245-325 K
CoSMIR T_N=500 K	325 K	245 K	100-325 K
Sat. Rad. T_N=500 K	300 K	0 K	0-300 K
Sat. Rad. T_N=100 K	300 K	0 K	0-300 K

Temperature Error for P_h= -21.3 dBm

	Z_L=200 O	Z_L=125 O	Z_L=50 O
CoSMIR Interpolated	0.06 K	0.01 K	<0.01 K
CoSMIR Extrapolated	16.2 K	1.6 K	0.02 K
Sat. T_N=500 K, Interpolated	0.83 K	0.13 K	<0.01 K
Sat. T_N=100 K, Interpolated	1.57 K	0.25 K	<0.01 K

Detector Summary

- Commercial tunnel-diode detector char.
  - Two-tone method with S.A. preferred
  - Single-tone with DVM as “sanity check”
  - Vary load impedance
- Bias point and Z_L optimization
  - Receiver dynamic range—T and T_N; interp/extrap.
  - Z_L ˜ 50 O (but not lower); consider $G_{op.\ amp}$
    - Potential improvement in ? T of 10X or more
    - 7 dB higher P_{in} for same ? T
    - Same Z_L on both op amp inputs to ?common-mode noise
    - Caution: might not apply to other detectors, and what happens at lower power levels?

Standard terminology for microwave remote-sensing radiometry—"Dictionary" project

- Analagous to vis/IR standard terminology handbook by NIST's Optical Technology Division
- Promote consistency in technical specifications, data exchange, and scientific discussions
- Essential preface to developing unambiguous uncertainty statements
- Developed in cooperation with CEOS WGCV
- Input & comments welcomed
- http://www.boulder.nist.gov/div813/stdterms/index.htm